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NON-DESTRUCTIVE TESTING FOR FIELD WELDS: REAL-TIME WELD QUALITY--ETC(U)
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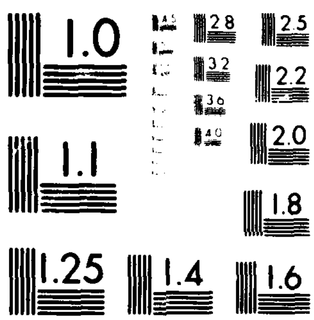

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LEVEL II

NON-DESTRUCTIVE TESTING FOR FIELD WELDS:
REAL-TIME WELD QUALITY MONITOR

JUN 1980

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1. INTRODUCTION

Background

During the welding process, changes in arc voltage, travel speed, and heat input can occur without the operator's knowledge. These changes can cause defects such as porosity, slag inclusions, incomplete fusion, and undercut in the deposited weld metal. The cost of locating and repairing these defects can be a major portion of construction costs; welding inspection can constitute 25 to 40% of the weld fabrication cost. In addition, weld defects decrease service life of welded joints.

Consequently, it is necessary to monitor the welding parameters to detect, identify, and locate possible defects. A weld monitor with real-time output would aid the inspector in designating suspect areas for non-destructing testing after welding. Further, a real-time weld quality monitor could be used to interrupt welding when defects are occurring thus precluding costly rework. To address this need, the US Army Construction Engineering Research Laboratory (CERL) is conducting research to develop a field-portable real-time weld quality monitor (WQM).

In the initial phase of the study, the following requirements were established for the device:

1. Monitor the three primary signals from the weld system: arc voltage, current, and travel speed; compare them to preset limits; and alert the operator if the limits are exceeded.

2. Calculate the heat input, nugget area, and cooling rate from the three primary signals; compare these values with preset limits; and alert the operator if these limits are exceeded.

3. Be field portable.

4. Interface easily with in situ welding equipment.

Essentially, the WQM is intended to provide a mechanism to merge the welding engineer's design intent with the actual field welding process.

Following delineation of these requirements, a prototype WQM was designed, fabricated, and tested using input from a fully automatic gas metal-arc (GMA) welding machine. The automated GMA process was chosen to obtain close control and reproducibility of the welding variables for initial testing.

Objective

The objectives of the first phase of the study were (1) to configure a portable, real-time WQM system, and (2) conduct laboratory and field tests to determine the adequacy and field applicability of the design.

Approach

The design of the breadboard WQM was modified to incorporate improvements indicated by actual welding situations in the laboratory. Hardware was assembled and packaged for field use.

In the transitional period from laboratory prototype to field prototype, personnel in Government and the private sector were consulted and their suggestions were used to further improve the unit. The unit was then installed in a welding situation that would thoroughly test all modes of operation.

2. FACTORS AFFECTING WELD MECHANCIAL PROPERTIES

In the development, testing, and evaluation of the various generations of the weld quality monitor, certain basic welding parameters and relationships were used as guidelines.

Defects

Changes in the welding parameters of arc voltage, travel speed, and heat input can cause several types of defects of deposited weld metal.

Porosity is a void or gas pocket trapped in solidifying weld metal. The reduced solubility of the gas in the metal caused by the decreasing temperature forces the gases out of solution. The gases are originally introduced either by poor shielding, which contains air, or by chemical reactions in the molten weld metal. With stick electrodes, too long an arc resulting from excessive arc voltage can reduce the shielding effectiveness, thus introducing gas.

Slag inclusion is the entrapment of an oxide or other nonmetallic material under the weld beam. The major source of slag is the coatings on stick electrodes. This defect is related to heat input.

Incomplete fusion is the failure of adjacent layers of the weld metal or weld base plate to fuse. Incomplete fusion may result when the adjacent metal is not heated to the melting point because of insufficient heat input.

An undercut is a groove melted into the base plate at the toe of the weld and is caused primarily by excessive travel speed in relation to the welding current.

In addition to the defects caused by improper control, the heat generated by the welding process can cause the following changes in the base metal:

1. Grain Coursening
2. Softening ("Annealing effects")
3. Hardening (Phase precipitation or transformation)
4. Segregation of constituents
5. Grain boundary melting
6. Loss of ductility
7. Loss of toughness

8. Residual stresses causing distortion or cracking.

The type of change which occurs depends on the chemical composition of the base metals and electros and heat history of the base plate.

In the two commonly used field welding processes -- shielded metal-arc (stick electrodes) and gas metal-arc (bare wire) -- the source of heat for melting the material is an electric arc. Control of the arc parameters will control the amount of heat generated, the length of time at an elevated temperature, and the cooling rate of the weld zone.

Base Metal Microstructure

The cooling cycle after a weld pass determines the microstructure of the weld metal and the heat-affected zone. With fast cooling rates, some steels become very hard because of a martensitic transformation. If the cooling is sufficiently slow, the metal may be more ductile and the structure ferritic and pearlitic. The type of steel generally determines which of these structures is desired. For low-carbon and low-alloy steels, the pearlitic structure is desirable, while for high-strength quenched and tempered steel, the martensitic structure is desirable.

Martensite is undesirable in low-carbon and low-alloy steels designed for yield strengths less than eighty ksi (552 MN/m^2) because of its hardness and low solubility for hydrogen at ambient temperatures. The combination of characteristics increases the likelihood of hydrogen cracking in the joints. Use of low hydrogen (stick electrodes) the gas metal-arc welding system reduces this tendency towards hydrogen-induced cracking.

Cooling Rate Control

Control of the cooling rate is essential in preventing undesirable microstructure in the weld and heat-affected base plates. A mathematical combination of arc voltage, current, and travel speed known as heat input (HI) has been used as a means of controlling cooling rates for many years. The equation for calculating heat input is:

$$HI(J/in.) = \frac{\text{VOLTAGE x AMPERAGE x 60}}{\text{TRAVEL SPEED (in./min.)}} \qquad [Eq\ 1]$$

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The normal maximum has been 55 thousand to 60 thousand Joules/inch. (21,654 to 23,622 J/cm) for the field processes mentioned above. Another means of controlling cooling rate has been preheat treatments. Dorschu [1] has shown that the relationship between heat input, preheat temperature, and cooling rate is:

$$CR = \frac{m\,(T - T_o)^2}{HI} \qquad \text{[Eq 2]}$$

Where CR = cooling rate

T = test temperature

T_o = preheat temperature

CR = cooling rate

c = constants

HI = heat input

Equation 2 indicates that the higher the preheat temperature and heat input, the slower the cooling rate.

Shultz and Jackson [2] have shown that the cross-sectional area of the weld bead is a useful indicator of weld metal mechanical properties and that a relationship exists between the area and cooling rates. They also found that arc voltage has little or no effect on the nugget area and cooling rate. The relationship that Schultz and Jackson have developed for nugget area, arc current, and speed is:

$$na = 122 \times 10^{-7} \frac{i^{1.55}}{S^{.0903}} \qquad \text{[Eq 3]}$$

where na = nugget area (sq. in.)

i = arc amperage

S = arc travel speed (in./min.)

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3. CIRCUIT DESCRIPTION

Figure 1 is a block diagram of the weld quality monitor showing the input signals from the welding arc. These signals are conditioned to standard values and sent to the comparator module, which compares the input signals with a set of limit signals. If the input signals are too high or too low, the appropriate alarm is triggered. Input signals are also transmitted to the analog computer module for calculation of the heat input, cooling rate, and nugget area. The calculated values are then compared to reference signals and the appropriate alarm is triggered if needed.

4. LABORATORY TESTS

Procedure

Each channel of the laboratory prototype monitor was individually tested with a variable signal similar in current and voltage level to the signal from a welding machine. The limits for each channel were set, and the test of voltages were varied to simulated changes in the primary signal.

After each channel was tested successfully, the three simulated primary signals were fed into the monitor simultaneously. The limits were again set and the input voltages varied. All circuits including the analog computer section were checked for accuracy and reproducibility.

The monitor was then connected to the CERL welding machine to test the circuitry with actual signals after the limits were set; the welding arc was established on a test plate.

Results

Results of the laboratory testing showed that all channels performed satisfactorily both independently and in conjunction with each other. The warning lights were triggered when the input signal exceeded the limits set by the reference signal, and no difficulties were encountered when the limit spans were changed.

While investigating the signals of the three parameters (voltage, current, and speed), it was found that the voltage and amperage signals contained spurious noise signals. These signals were removed by (1) incorporating filters in the data channels to

eliminate the peaks and smooth out the signals, thus reducing the chance of damage to components, and (2) replacing the shunt as the amperage signal source with a Hall effect solid state transductor. (The advantage of using the transductor is that it is not directly connected to the welding machine as the shunt is; instead, it fits around the cable and measures the magnetic field generated by the current passing through the cable.) The transductor minimized amperage transient signal problems; filters were installed in all channels in field contingencies. The modifications indicated by the laboratory testing program were incorporated into the monitor before field testing.

5. FIELD TEST

Site Selection

The general types of welding operations considered for field testing were shop fabrication which uses automated welding equipment and field fabrication/repair which involves manual or semi-automatic welding and is more dependent on the operator's subjective judgment.

In addition, it was decided that field tests would be more conclusive if the weld quality monitor were used in conjunction with some other form of non-destructive testing. Two sites were available that offered these combinations: Flint Steel Corp., Tulsa, OK, and a hydro-electric turbine shaft repair job at Ozark Hydro-Electric Plant, Ozark, AR. The field repair job at Ozark power plant was chosen since it would entail situations that could not be simulated during the CERL laboratory evaluations. It was felt that the time and space constraints of the field repair situation would assess the unit's adaptability most rigorously. In addition to the hardware evaluation, the field test would provide an opportunity for welding personnel from industry to appraise the WPM.

Test Operations

The WQM and auxiliary equipment were transported from CERL to the Ozark plant in a conventional automobile with no special handling. The equipment was set up by maintenance personnel and was ready for operation in less than one day.

The WQM was set up approximately 50 feet (15 m) from the repair location. Installation of this device involves simple

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disconnection and reconnection of one of the leads from the welder power unit; no hard wiring is required.

Since no speed measurement system was available for this test, a precision voltage source was used to provide an equivalent signal to compute heat input and nugget area. For this mode of operation, a voltage corresponding to a particular welding speed is input to the analog computer module to compute heat input in nugget area (equations 1 and 3). For example, if the analog module were scaled for one volt equal one inch per minute, then a six-volt signal from the precision voltage source would be input for a welding speed of six inches per minute.

The signals taken at the output of the signal conditioners before filtering for inputting the comparators are not distorted, and the response of the sensors to the voltage and current variations incurring in the arc is preserved in the transduction and the conditioning process. Thus, several data utilization options are possible -- from simple alarms to adaptive control systems.

Results

The central unit and associated sensors were interconnected and energized without disrupting the welding contractor or requiring welding equipment modification. This verified the adaptability and flexibility of the design objective. Installation of the system was accomplished by a ceramic engineer; an electrical engineer was not required.

The WQM was operated by non-electronic personnel (a welding engineer) with minimal instruction. The data display and printout were understandable to both laboratory and contractor personnel.

During the start up of the WQM, erratic operation was indicated by the visual display; the modular packaging method enabled the problem to be diagnosed and repaired rapidly by interchanging modules. Again, this was accomplished by non-electronic personnel using predefined trouble-shooting procedures.

With the feasibility of the design intent of the WQM demonstrated, a concerted program was initiated to develop: (1) suitable speed-measuring systems for manual welding situations, (2) specific radiometric measurement techniques involving acoustic emission and thermal spectral analysis, and (3) digital processing features using microprocessor to facilitate programming the WQM.

6. OPTOELECTRONIC WELD EVALUATION

Direct quantitative measurements of certain parameters of welds in process have not been possible for several reasons. In particular:

a. The high weld temperatures consume and destroy sensors proximate to the weld area.

b. Contacting sensors introduce a discontinuity of the weld process causing data of uncertainty.

c. In the case of manual welding, the subjectiveness peculiar to the welder is indeterminant and variable.

Presently, some indirect measurements are utilized such as thermocouples, etc., but these techniques exhibit time lags, averaging effects, and other factors that mitigate the validity and reproducibility of the information obtained.

Because of this inability to measure directly and instantaneously the quantities relevantly to a satisfactory weld, a research program was implemented to produce non-contacting instrumentation techniques that will be field applicable to directly monitor pertinent weld measurements such as cooling rate, weld speed, and heat input, to serve as input data to the CERL weld quality monitor.

Optoelectronic technology is used to detect the amplitude and wave length of radiation emitted by the welding arc. A photodector, or an array of photodectors is the primary sensor with appropriate circuitry to provide the required output information.

Physics of Welding Arc

For all practical purposes, the welding arc can be thought of as a gaseous conductor which changes electrical energy into heat. The welding arc can be defined as a particular group of electrical discharges that are formed and sustained by the development of a gaseous conductive media. The current carriers for the gaseous medium are produced by thermal means and field emission.

The arc current is carried by the plasma, the ionized state of a gas composed of nearly equal numbers of electrons and ions.

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Mixed with the plasma are other states of matter, including molten metals, slags, vapors, neutral and excited gaseous atoms and molecules.

Measured values of welding arc temperatures normally range between 5,000 and 30,000 degrees K, depending on the nature of the plasma and the current conducted by it.

The amount and character of spectral radiation emitted by arcs depend fundamentally upon the atomic mass and chemical structure of the gas, temperature, and the pressure. Spectral analysis of arc radiation will show bands, lines, and continua. The analysis of radiation from organic-type covered electrodes shows molecular bands due to the existence of vibrational and rotational states as well as line and continuum emission from excited and ionized states. The inert gas arcs radiate predominately by atomic excitation and ionization. As the energy input to arcs increase, higher states of ionization occur, giving radiation from higher energy levels.

The fundamental method utilized in the development of noncontacting sensors in this study is to separate and quantify segments of weld spectra correlatable to specific weld parameters. The visible spectrum and a portion of the infrared spectrum emanating from the argon-shielded gas tungsten arc are shown in Figure 2.

Optical Electronic Transduction Methods

Two methods of segmenting or partitioning weld spectrum are: Selection of photosensors having a spectral response only in sections of the spectrum to be measured and, use of optical filters to limit the wave length of radiation impinging on the photodector. For this work, the latter method was used; the radiation physics and adaptation of the optical electronics to the problem is illustrated in Figure 3. Extreme flexibility was provided by various combinations of commercial photographic filters which made it possible to segment the arc spectra into approximately five bands which provided adequate resolution to quantify weld flaws. Two examples will briefly illustrate the procedure.

An analysis of the metallurgical phase diagrams associated with weld nugget area suggested that the normal (acceptable) weld spectrum and a deviant spectrum characterizing a flaw would have wave lengths greater than 700 nanometers. To implement the "front end" of the sensor system, a Wratten type 89b filter was

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selected coupled with a type TIL-63 phototransistor. This provided a sensor system with a photometric "window" of approximately 700-1,050 nanometers; thus, the desired spectra were detected while extraneous spectra were attenuated. A fiber optic light pipe was the transmission device between the arc and the phototransistor. Weld arc instability or "sputtering" is one of the most common flaw-inducing conditions encountered in practice. Laboratory testing using radiometers indicated that spectral lines omitted by an unstable arc were very dense in the visible range; to quantify this, a ratton 57 cylinder was used in the front end with notable results. Another flaw-inducing condition that was detected by this "poor man's photometer" was magnetic arc blow. Present work is concentrated on developing rugged temperature high optical systems to provide durability for field use. To date, the results are most encouraging; the fiber optic bundles are 1/16 to 1/8 inch diameter and fortuitously have a pass band in the range required, specifically .4 nanometers to 1.9 nanometers.

7. Large Scale Integration (LSI) and the WQM

The primary factor that makes the WQM a practical and ubiquitous tool is the confluence of welding engineering and large-scale integration electronics technology. Measurements and recordings of voltage, current and, more recently, acoustic emission data is becoming quite standard. The CERL WQM is innovative and unique in that it utilizes this data for <u>in-situ</u>, <u>real-time</u> analysis for <u>continuous</u> and <u>instantaneous</u> quality assurance.

8. Epilogue

Concurrent with the submission of this paper, the first successful tests of a prototype optoelectronic system configured for field use were conducted at CERL.

In this unit the spectrum is segmented and quantified by a grooved spectrograph and linear photodiode array. A high temperature fiber optic bundle is routed along the flexible cable/hose assembly to the welding gun and does not interfere with normal welding operations. Because of this versatility, the system is applicable to manual welding which is the principal method used by the Army.

Flaws caused by slag inclusions, loss of flux, loss of cover gas and magnetic arc blow have been distinctly characterized.

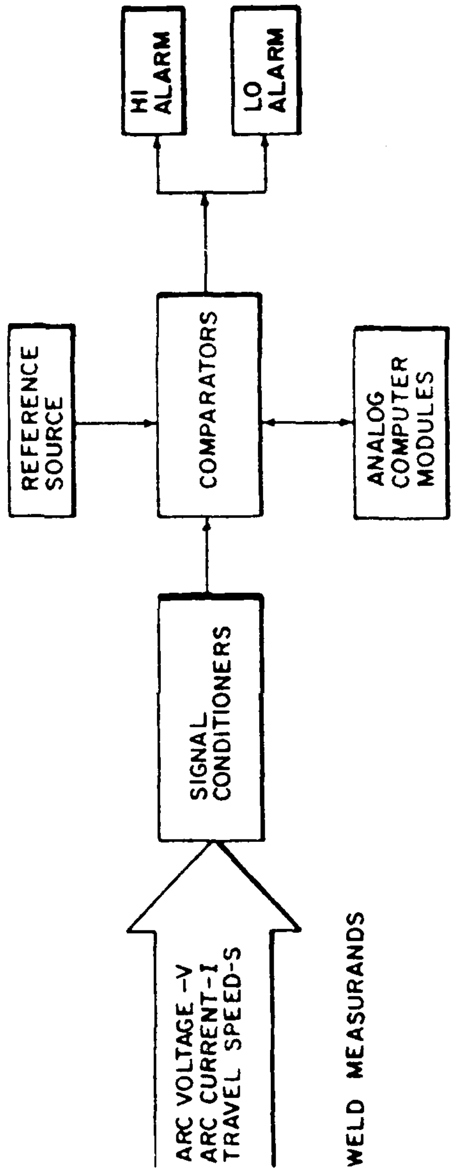

FIG. 1 BLOCK DIAGRAM OF WELD QUALITY MONITOR

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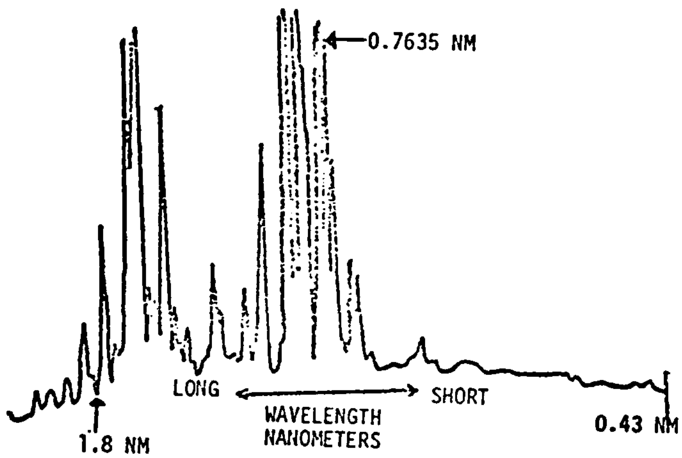

FIG. 2 SPECTRUM OF THE ARGON SHIELDED GAS TUNGSTEN ARC
ARGON ARC 3mm (1/8 in.) DIAMETER PURE
TUNGSTEN ELECTRODE 200 AMP (ELECTRODE POSITIVE)

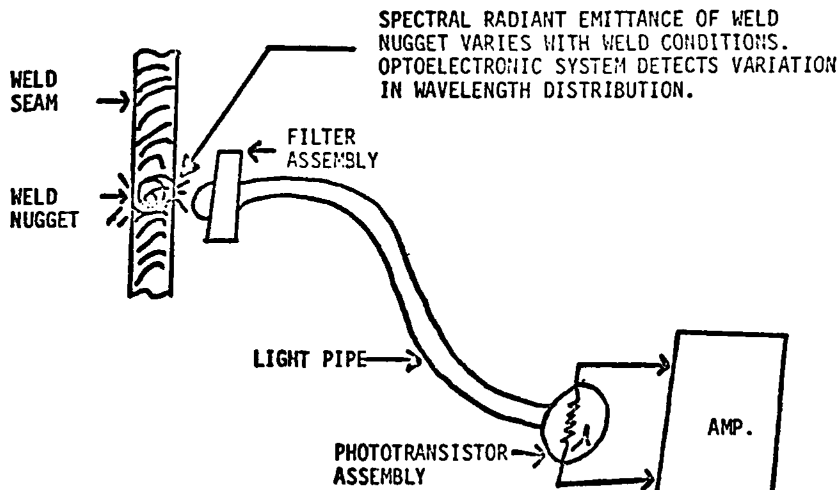

FIG. 3 OPTOELECTRONIC SYSTEM AND APPLICATION TO WELDS

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